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Risk assessment of soil heavy metals in mining activity areas: a case study in Eastern Shandong Province, China

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Abstract

A total of 237 surface soil samples were collected during May and June 2021 within a mining activity area in Eastern Shandong Province, China. In this research, the soil heavy metal pollution risk and its sources were identified in the mining activity area. Overall, the soil was acidic in nature, and most of the sites were uncontaminated, except for a few that were slightly polluted. The heavy metals produced by mining activity were mainly Hg, Pb, and Cd, among which Hg was highly enriched, while Pb and Cd were slightly enriched, indicating high ecological risks for Hg followed by Cd in this region. Most of the heavy metals were not above the detrimental level for human health, but the As, Cr, and Pb contents require attention. The Ni and Cr heavy metals were mainly derived from natural sources, whereas As was derived from pesticides and fertilizers, Zn and Cu had mixed sources, and the heavy metal Cd may affect agricultural security to some extent. This study provides scientific support for implementing policies to control heavy metal pollution and its sources. These findings will also assist in protecting and restoring the ecological environment, promoting safer agricultural production, and providing a healthier life for residents within mining activity areas.

Keywords Soil heavy metals · Mining activity areas · Risk assessment · Ecological environment · Human health · Agricultural security

Introduction

A healthy soil is critical for agriculture and daily life (Wanjala et al. 2020; Wang et al. 2022b). Soils are becoming increasingly polluted with heavy metals as a result of rapid economic and social growth, endangering the ecological environment, agricultural food safety, and human health (Yang et al. 2020; Li et al. 2022; Tran et al. 2022). Heavy metal contamination of soil has a major impact on human health, attracting the attention of researchers (Xu et al. 2017; Zhao et al. 2020). Soil heavy metal contamination due to human activities has become a worldwide issue (Solgi et al. 2012; Ma et al. 2015; Adnan et al. 2022).

Arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn) are the most common heavy metals found in soil (Liu et al. 2019). The United Nations Environment Programme has identified these eight heavy metals as priority contaminants that must be addressed (Giller and Mcgrath 1988; Rodrigues et al. 2013). Soil heavy metals are thought to originate from two main sources: (1) natural sources (for example, volcanic activity, forest fires, and the weathering of rocks and minerals in soils), when the soil heavy metals are typically present at low levels and are not readily absorbed by plants, and (2) human-caused sources, including industrial processes, mining activities, sewage irrigation, air pollution deposition, and the excessive use of pesticides (Yang et al. 2013; Fei et al. 2019).

Soil heavy metal pollution is common in most metal mining locations (Gallego et al. 2015; Li et al. 2017). Heavy metal pollution in mining areas is mostly produced by heavy metal discharge and leakage during mining operations, and it eventually accumulates in the soil (Gong et al. 2008). High concentrations of heavy metals in soil are usually linked to a variety of problems via multiple ingestion pathways, such as a reduction in animal communities, poor crop and plant

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growth, and human health threats, due to their high toxicity, persistence, accumulation, and irreversibility (Lin et al. 2018; Wang et al. 2018; Zhang et al. 2021a, b). Heavy metals in soil can enter rivers and reservoirs through natural cycles or human activities, resulting in large cumulative areas of polluted water and soil (Pruvot et al. 2006), which further harms the ecological environment, agricultural production, and human health within the associated drainage basin (Cardwell et al. 2002; Nabulo et al. 2010). As a result, it is critical to conduct risk assessments of soil heavy metal contamination inside mining sites to regulate and mitigate severe heavy metal pollution. Such risk assessments are essential for decreasing heavy metal contamination in soil (Zhao et al. 2022).

A substantial quantity of related research has been undertaken in recent years. González-Méndez et al. (2022), for example, evaluated the spread and causation of heavy metal contamination along the Sonora River, which originated from an abandoned mine in Sonora, northwest Mexico. Tran et al. (2022) evaluated soil heavy metal contamination along rivers in a mining area as well as the human health concerns connected with these heavy metals. Huang et al. (2018) investigated the speciation distribution characteristics of soil heavy metals along rivers around the Sunan mining area and analyzed the associated ecological concerns. Furthermore, Liu et al. (2013) investigated the speciation of heavy metals in soil and the pollution of agricultural soils in a non-ferrous metal mining area, as well as the impact on agricultural security. These studies discussed the effects of soil heavy metals originating from mining activities on the watershed, and some analyzed a specific aspect of the associated risks; however, information about the content, contamination, and speciation of soil heavy metals was not combined to enable a comprehensive analysis of the effects on the ecological environment, human health, and agricultural security.

To provide such a comprehensive analysis, we selected a mining area within a small drainage basin in Eastern Shandong Province, China, as the study area. The heavy metal contamination in this region and its sources were identified, and risk assessments for these heavy metals were undertaken in terms of their impact on the ecological environment, human health, and agricultural security. These findings will help policymakers implement new regulations addressing soil heavy metal pollution, ecological protection and restoration, and safe agricultural production. They will also help promote the health of the population in this area.

Materials and methods

Study area

The study area (about 56.1 km^2) is located in a mining activity area in Shandong Province, China (Fig. 1a), which occupies a monsoon climate, and four distinct seasons, and with average annual temperature (11.9 °C) and rainfall (680 mm). Plains and hills dominate the landscape, with the north being higher in height than the south. Orchards (pears and apples) and cultivated land are the two most common types of land use (wheat and peanuts). The study region is rich in natural resources, including gold, granite, marble, diopside, and a variety of other minerals. Gold is the most common mineral among these. This region's industrial mining activities are well-developed, and include mining, mineral processing, ore smelting, and waste treatment.

The mining activity in the study area can be traced back to the end of the Qing Dynasty, and after more than a century of production and development, heavy metals likely remain in the soil due to previous mining activity. The reservoir, located south of the mining activity area, is an important water source for the region. Two rivers flow through the mining activity area and eventually falls out into the main stream. The heavy metals enter the rivers via natural circulation and human activities and then spread to the reservoir and soils, ultimately affecting the ecological environment, human health, and agricultural production in the drainage basin.

Sample collection and measurement methods

Sample collection and preparation

To conduct this study, 237 surface soil samples were collected in the study region during May and June of 2021. The sampling density was four sampling points per square kilometer, and 217 samples were collected to assess the heavy metal content. In addition, 20 samples were collected for heavy metal fractionation analysis from the farmlands around the mining activity area. An overview of the sampling points distribution can be found in Fig. 1b.

The global positioning system was used to geolocate all sampling locations. Five sub-samples were obtained from the top 0–20 cm soil layer within a 5-m radius of each sampling point and mixed uniformly to make composite sample. After removing stones and grass, samples were analyzed in the laboratory.

Measurement methods

Different fractions of the soil heavy metals were determined according to the Sequential Extraction Procedure (SEP) given in DD2005-03 (China Geological Survey 2005). The water-soluble fraction, ion exchangeable, carbonate-bound, weak organic matter-bound, Fe–Mn oxide bound fraction, strong organic matter-bound and residuals fraction, Fig. 2, provides a schematic representation of the SEP of different fractions (Wu et al. 2022; Wang et al. 2022c).

Fig. 1 Location of the study area and distribution of soil sample sites. **a** Location of the study area. **b** Distribution of soil sample sites
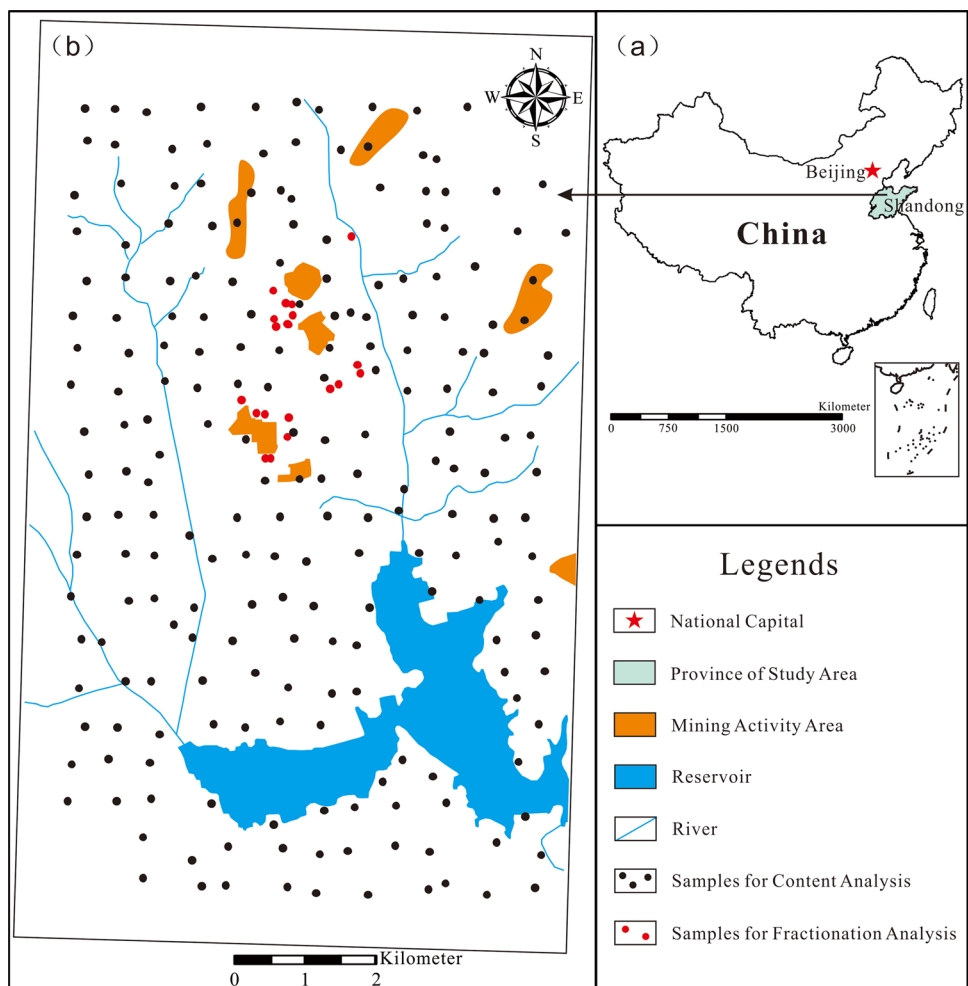
The heavy metal content of the soil were determined adopting Rock Mineral Analysis (DZG20.01-2011) procedure (Committee of Rock and Mineral Analysis 2011). The amounts of Pb, Cd, Cr, Cu, Ni, and Zn in soil samples were determined using inductively coupled plasma mass spectrometry (ICP-MS) (Wang et al. 2022a, b), whereas the concentration of As was determined using hydride generation–atomic fluorescence spectrometry (HG–AFS) (Wang et al. 2022a, b). Similarly, for determination of Hg Cold vapor generation–atomic fluorescence spectrometry (CV–AFS) was used (Fei et al. 2022; Adnan et al. 2022; Yang et al. 2022). The soil pH was measured using an ion-selective electrode.

Contamination assessment

Single factor index assessment

Based on the national risk screening values (S_i) and risk intervention values (G_i) set in GB 15618-2018 (Ministry of Ecology and Environment of China 2018), the contamination degree of single soil heavy metal could be evaluated.

The S_i and G_i are shown in Table S1, and the assessment standards are shown in Table S2.

Nemerow comprehensive index assessment

The Nemerow comprehensive index assessment which made the inductive calculation of the average value and the maximum value of the single factor index was used to evaluate the level of contamination (Nemerow 1974). Both average and maximum values are combined in this method. The formulas for this calculation are as follows:

$$P_i = \frac{C_i}{S_i}$$

$$P_N = \sqrt{\frac{P_{max}^2 + P_{ave}^2}{2}}$$

where C_i is the measured value, S_i is the risk screening value, P_{max} and P_{ave} represent the maximum value and average
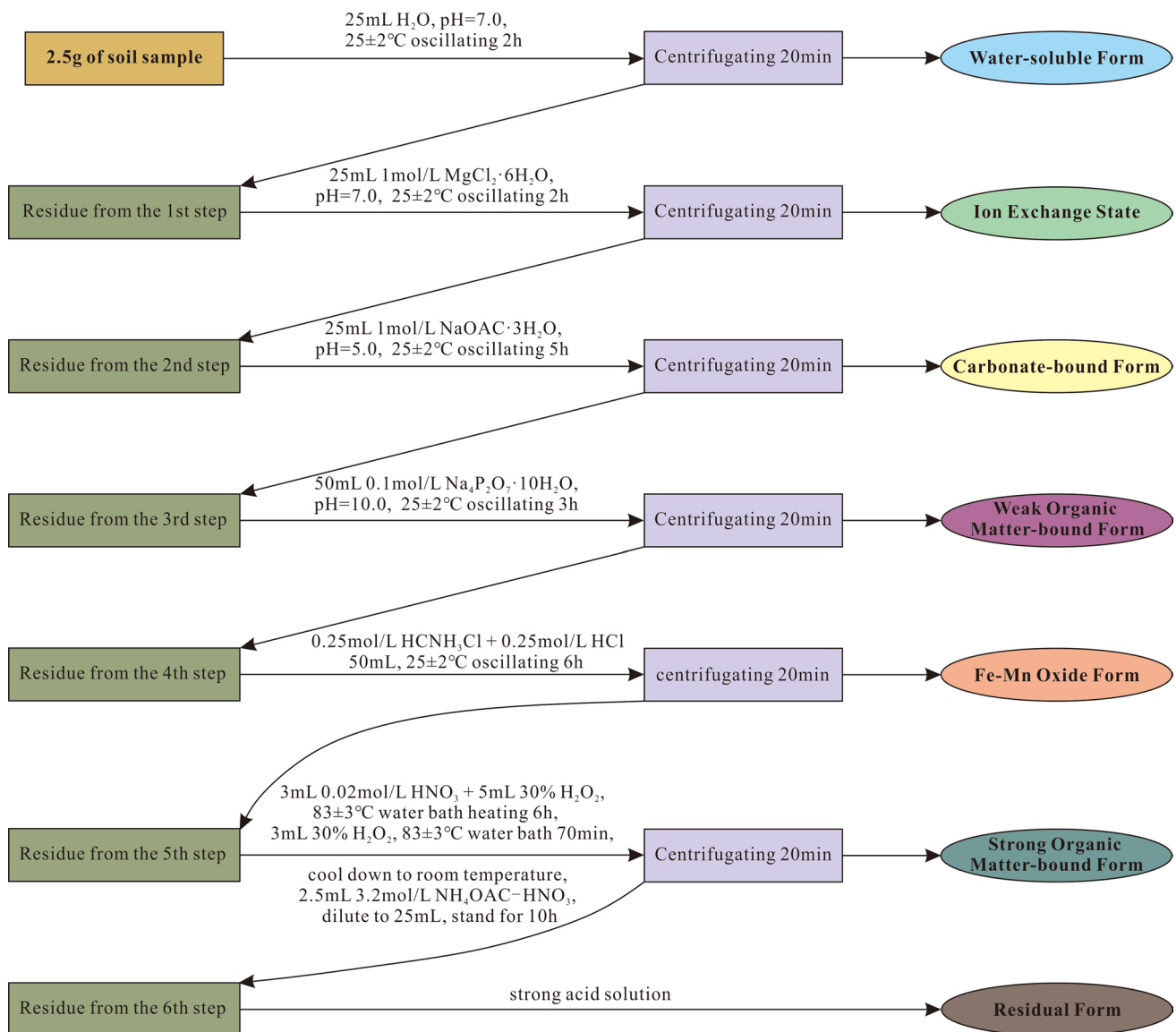
Fig. 2 Schematic representation of SEP

value of P_i, respectively, and P_N is the Nemerow comprehensive index. Table S2 shows the evaluation standards of the Nemerow comprehensive index.

Geological accumulation index assessment

Müller (1969) was the first to propose geological accumulation index (I_{geo}) method. Since that it has been broadly used for the assessment of heavy metal contamination in sediment and soil. The calculation method of I_{geo} is as follows:

$$I_{geo} = \log_2 \frac{C_i}{1.5 B_i}$$

where I_{geo} represents the geological accumulation index, C_i is the measured value, and B_i stands for the background concentration (adopted from the local geochemical background concentration of the soil (Pang et al. 2014). The pollution classification standards of I_{geo} are shown in Table S3.

Potential ecological risk index analysis

Hakanson (1980) had proposed a method to evaluate the influence of heavy metal toxicity on ecological environment known as potential ecological risk index. The equations for this method are as follows:

$$E_r^i = T_r^i \times \frac{C^i}{C_n^i}$$

$$RI = \sum_{i=1}^{n} E_r^i$$

where E_r^i represents the potential ecological risk index of a single heavy metal, C_i is the measured value, C_n^i is the evaluated value (adopted from the local geochemical background concentration in the soil (Pang et al. 2014), T_r^i is the toxicity factor (Hg = 40, Cd = 30, As = 10, Pb = Ni = Cu = 5, Cr = 2, Zn = 1) (Xu et al. 2009), and RI represents the comprehensive potential ecological risk index of multiple heavy metals. The evaluation standards are listed in Table S4.

Human health risk assessment

Soil heavy metals enter into the human body mainly via three routes: ingestion, inhalation, and dermal absorption. Due to the toxic nature of the heavy metals, human exposed to it may have serious health risks. The daily intake through the three mainly pathways can be calculated as follows:

$$ADD_{\text{iing}} = C_i \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6}$$

$$ADD_{\text{iinh}} = C_i \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT}$$

$$ADD_{\text{iderm}} = C_i \times \frac{SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6}$$

where ADD_{iing}, ADD_{iinh}, and ADD_{iderm} represent the average daily intake dose of the single heavy metal via the ingestion, inhalation, and dermal absorption, respectively, and C_i is the measured value. The other parameters and their reference values are listed in Table S5 (USEPA 2011; Ministry of Environmental Protection of China 2014; Wang et al. 2008).

Based on the soil health risk model given by the United States Environmental Protection Agency (USEPA 2011), the following formulas are given to evaluate both non-carcinogenic and carcinogenic health risks to human body from soil heavy metals:

$$HI = \sum HQ_{i,j} = \sum \frac{ADD_{i,j}}{RFD_{i,j}}$$

$$CR = \sum CR_{i,j} = \sum \left(ADD_{i,j} \times SF_{i,j} \right)$$

where CR and HI are carcinogenic risk and non-carcinogenic risk, respectively. When heavy metal i is absorbed by the human body through pathway j, HQ represents the non-carcinogenic risk and $CR_{i,j}$ represents the carcinogenic risk. $ADD_{i,j}$ represents the actual average daily intake dose, $RFD_{i,j}$ denotes the average daily intake reference dose, and $SF_{i,j}$ is the carcinogenic slope factor. Reference values for each parameter are shown in Table S6 (Ministry of Environmental Protection of China 2014).

Previous studies (Mohammadi et al. 2020; Fei et al. 2022; Peng et al. 2022; Wei et al. 2022; Zhao et al. 2022) have indicated that the non-carcinogenic risk could be negligible when $HI < 1$; and, when $HI \geq 1$, it indicates negative effect on human health. The carcinogenic risk can be divided into a low level ($CR < 10^{-6}$), an acceptable level ($10^{-6} \leq CR \leq 10^{-4}$), and an unacceptable level ($CR > 10^{-4}$).

Mobility factor

The toxicity of heavy metals in soil to plants is not solely determined by total concentration in soil. It is more dependent on the content and type of plant available fraction. The mobility factor, allow the degree of risk to crops from soil heavy metals (Yu et al. 2019). In general, the water-soluble form, ion exchange, and carbonate bound fractions are easily utilized by crops plants. The mobility factor can be calculated with following equation:

$$M_F = \frac{B_1 + B_2 + B_3}{B_1 + B_2 + B_3 + B_4 + B_5 + B_6 + B_7}$$

where B_1–B_7 are the contents of the water-soluble form, ion exchange state, carbonate combined form, weak organic matter-bound form, Fe–Mn oxide form, strong organic matter-bound form, and residual of the soil heavy metals, respectively.

Statistical analysis

All images and maps were created with Arcgis 10.2, Coreldraw × 8, Surfer 14, and Microsoft Word 2016's built-in mapping program. Microsoft Excel 2016 was used to perform descriptive statistical calculations. Correlation analysis and principal component analysis were performed using IBM SPSS Statistics 26.

Results

Characteristics of soil heavy metal concentration

Soil heavy metal content distribution and pH values in the study area are shown in Fig. 3. The following is evident: (1) the As contents were uniformly distributed throughout the study area, except a single point with high values; (2) in the middle and eastern parts of the study area Hg, Pb, and Cd enrichment was quite similiar and nearly overlapping; (3) distribution of Cr and Ni contents were similiar
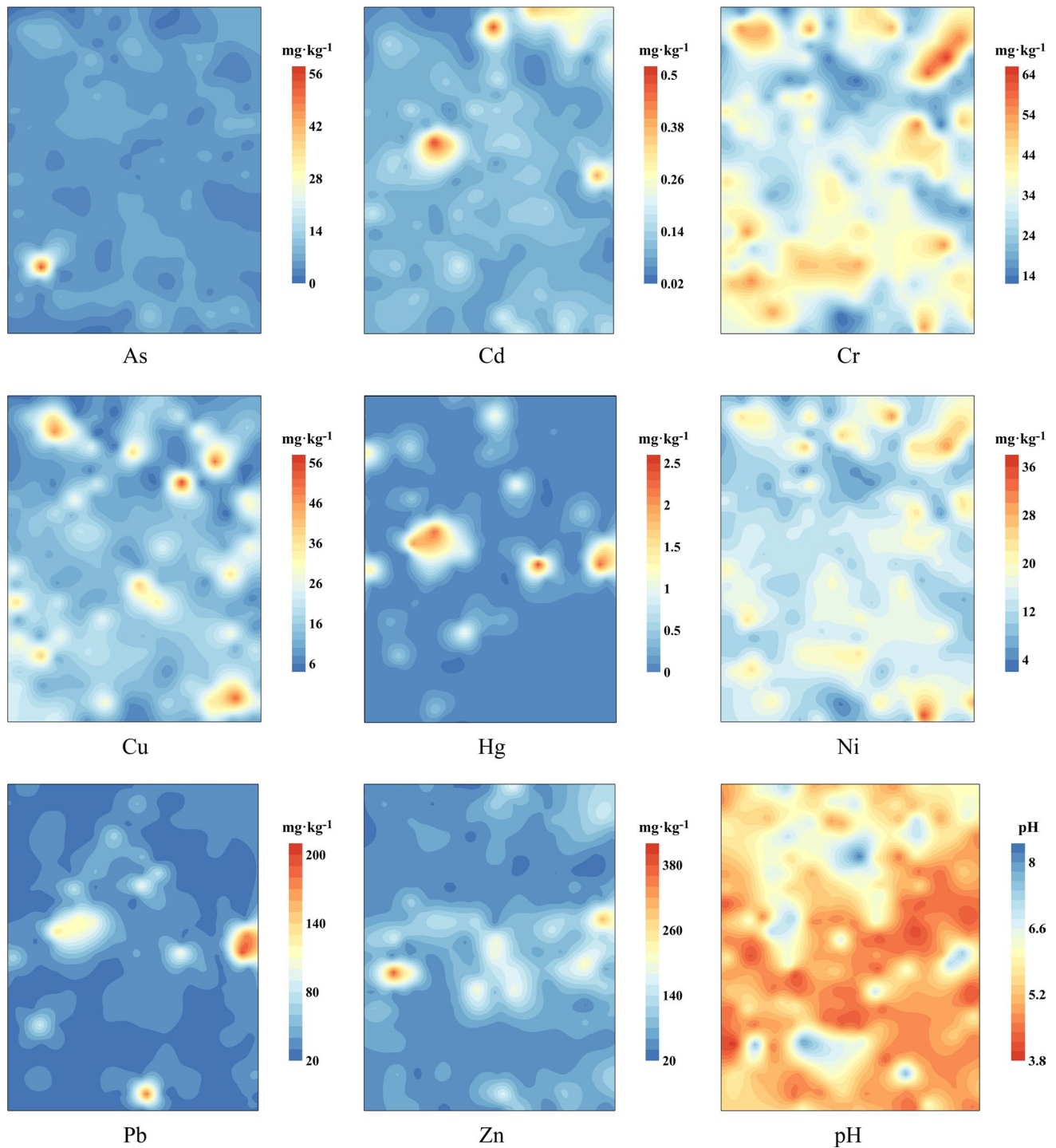

Fig. 3 Distribution map of soil heavy metal content and pH values in the study area

to each other and high Cu contents were in the same areas; (4) the middle part, Zn was enriched, but the high-value areas were different from those of Hg, Pb, and Cd; and (5) the soil had a generally low pH, and ranged between 3.85 and 8.31, with average value (5.38) which was lower than the surrounding values (6.60). Hence, the soil was slightly acidic (Table 1).

The average content of all eight soil heavy metals was below S_i, indicating that the soil in this area did not appear to be seriously contaminated by heavy metals (Table 1 and Fig. 4). The average concentrations of Hg (6.07), Zn

(1.60), Pb (1.51), and Cd (1.12) were higher than the background levels in the area especially Hg.

The coefficient of variation (CV) is the ratio of the standard deviation to the mean. In general, strong, moderate, and weak variation are considered as CV > 100%, $10\% \leq CV \leq 100\%$, and CV < 10%, respectively. Soil heavy metals variation (CVs) were in the following order as Hg > As > Pb > Zn > Cu > Cd > Cr > Ni (Table 1), CV of Hg was over 200%, indicating considerably uneven distribution across the surface soil varied, whereas the other heavy metals ranged between 49.85% and 72.57%, indicating moderate level of variation.

Table 1 Characteristics of soil heavy metal concentration in the study area

Heavy metals	Minimum value (mg kg^{-1})	Maximum value (mg kg^{-1})	Average value (mg kg^{-1})	Standard deviation	Coefficient of variation (%)	The local background value (Pang et al. 2014) (mg kg^{-1})
As	1	57.1	5.55	4.02	72.57	7.0
Cd	0.034	0.507	0.11	0.06	58.40	0.098
Cr	11.3	237	33.85	17.56	51.86	52.4
Cu	3.56	62.4	15.87	9.65	60.79	17.3
Hg	0.0005	2.647	0.17	0.38	223.56	0.028
Ni	3.12	85.2	14.49	7.22	49.85	22.5
Pb	20.2	199	36.57	24.10	61.31	24.2
Zn	30.5	400	76.78	48.94	65.90	48.0
pH	3.85	8.31	5.38	0.90	16.68	6.60

Fig. 4 Bar chart of soil heavy metal content in the study area

Note: Due to the average pH of soil was 5.38, the risk screening values of each heavy metal were selected which correspond pH < 5.5.
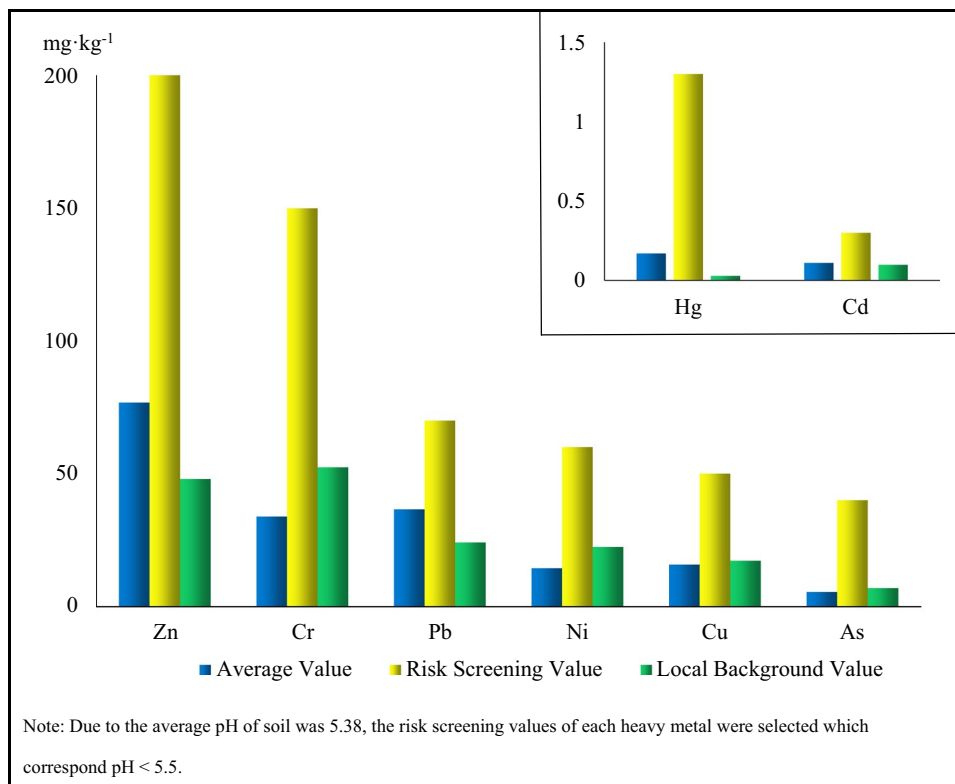
Table 2 Pearson correlation analysis of soil heavy metals

Correlation								
	Hg	As	Cr	Ni	Cu	Zn	Cd	Pb
Hg	1							
As	0.057	1						
Cr	− 0.051	0.095	1					
Ni	− 0.057	0.107	0.907**	1				
Cu	0.056	0.292**	0.516**	0.517**	1			
Zn	0.115	− 0.021	0.156*	0.198**	0.167*	1		
Cd	0.455**	0.077	0.104	0.140*	0.142*	0.206**	1	
Pb	0.677**	0.027	− 0.049	− 0.073	0.048	0.239**	0.459**	1

**At 0.01 level (two-tailed), the correlation was significant

*At 0.05 level (two-tailed), the correlation was significant

## Source identification of soil heavy metals

The sources of the soil heavy metals can be predicted through Pearson correlation analysis (Liu et al. 2019). If the concentrations of the soil heavy metals are found to be correlated, they may originate from the same source; otherwise, the sources are likely to be different. As listed in Table 2, there was a strong correlation ($0.6 \leq | r | < 0.8$) between the Hg and Pb concentrations and an extremely strong correlation ($0.8 \leq | r | < 1$) between Ni and Cr. Cd was moderately correlated ($0.4 \leq | r | < 0.6$) with Hg and Pb, as was Cu with Ni and Cr. The correlations were not obvious between the remaining soil heavy metals.

To further assess the sources, principal component analysis was applied on the basis of the Pearson correlation analysis, and the results were processed by maximum variance rotation. The Kaiser–Meyer–Olkin test value was 0.642 and the significance was 0.000, indicating that an analysis of principal components was possible with the data. The principal components whose eigenvalue was over 1, namely, the first three, were extracted. Their initial cumulative contribution rate reached 70.951%, which was reduced to 68.726% after rotation processing. Therefore, principal components (PC)1–3 were studied, the results of which showed the situation of essentially the whole region. The results of the principal component analysis can be seen in Table 3 and Fig. 5. The main soil heavy metals in PC1 were Ni, Cr, and Cu, and the minor component was Zn. In PC2, the main soil heavy metals were Hg, Pb, and Cd, Zn was also the minor. As was the main soil heavy metal in PC3, followed by Cu.

The principal component analysis results further verified that there was an extremely strong correlation between Ni and Cr in this region, and a strong correlation between Hg, Pb and Cd was also noted. Hence, the sources of Ni and Cr were roughly the same, as the sources of the Hg, Pb, and Cd.

Table 3 Component matrix of soil heavy metal content after rotation processing

Parameter	Principal component		
	1	2	3
Hg	− 0.083	0.849	0.071
As	0.171	0.101	0.883
Cr	0.928	− 0.039	− 0.044
Ni	0.939	− 0.031	− 0.052
Cu	0.712	0.120	0.334
Zn	0.329	0.357	− 0.425
Cd	0.165	0.730	− 0.002
Pb	− 0.068	0.872	− 0.039
Eigenvalues	2.307	2.080	1.111
Percentage of variance	28.834	25.999	13.893
Cumulative % Eigenvectors	28.834	54.833	68.726
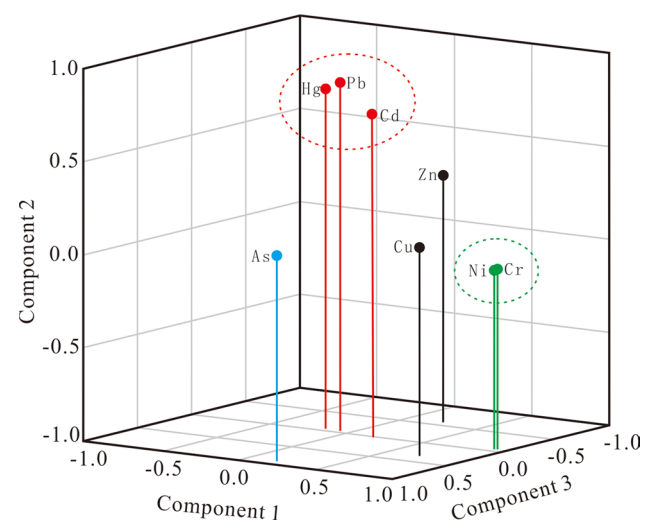
Fig. 5 Three-dimensional principal component analysis of soil heavy metals in the study area

Degree of soil heavy metal contamination

The majority of techniques use the ratio between the measured value and the reference value to assess soil heavy metal pollution. To manage land classification, Si should be chosen as the reference value, and to examine the enrichment of soil heavy metals, the local background value should be chosen. Both the Nemerow comprehensive index assessment and the single factor index assessment in this study used Si as the reference value, while the geological accumulation index assessment used the local background value.

Single factor index assessment and Nemerow comprehensive index assessment

The results of the single factor index evaluation are shown in Table S7. Most samples were risk-free, but few reached the risk screening value. Only one sample (Hg) went over Gi. The overall grade of soil environmental and geochemical conditions is the same as the lowest grade of each site's single factor index (MEE 2018). The classification of the soil environmental geochemistry in this area shows that 88.48% of the samples were graded as grade I (risk-free), 11.068% were grade II (controllable risk), and 0.928% (only one sample) were grade III (high risk) (Table S8). Overall, the soil was relatively free of heavy metal contamination from the perspective of land classification management; only a small portion was slightly polluted in this area. the Nemerow Comprehensive Pollution Index's findings. It is clear that 205 samples, or 94.47%, of the samples, fell within the safe or warning line, while 12 samples, or 5.53%, fell into the category of having light pollution. There were no samples that were moderately or severely polluted (Table S8).

Geological accumulation index assessment

The Igeo's results showed that Ni, Cr, and As were not enriched in this region, because only sporadic samples were found to be polluted and the contamination levels were all quite low. The enrichment of Hg was relatively high, with 35.48% of the samples classified as moderately contaminated to higher, and 74% samples were uncontaminated. The highest enrichment of Pb, Cd, Zn, and Cu was observed, and only a small percentage of the samples showed moderate to high levels of contamination (Fig. 6).

Risk assessment of soil heavy metal contamination

Potential ecological risk

Potential ecological risk index was used to evaluate the soil heavy metals ecological risks in this region. The potential ecological risk index of single soil heavy metal (As, Cr, Cu,
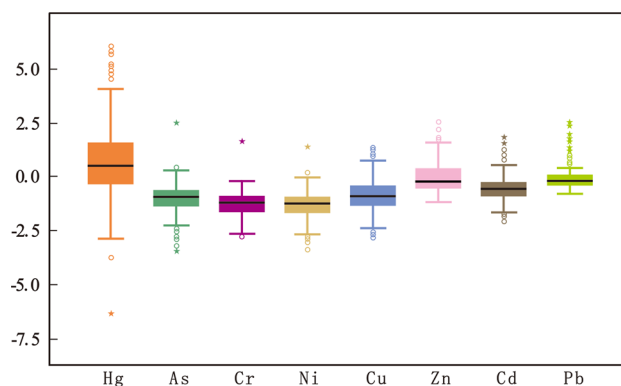

Fig. 6 Boxplots of the I_{geo} values for eight heavy metals in 217 soil samples
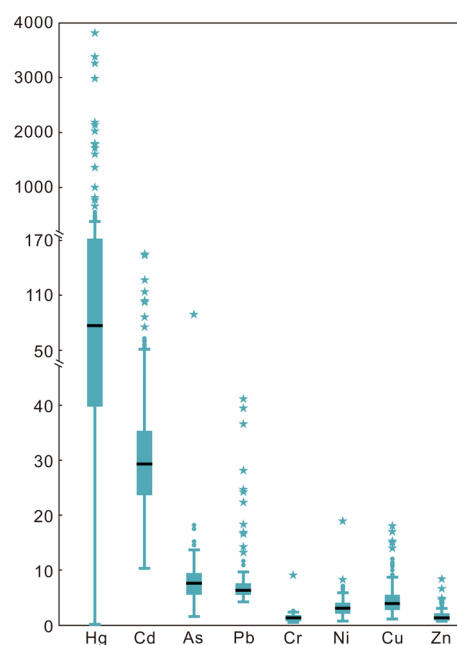

Fig. 7 Boxplots of the potential ecological risk of single soil heavy metal

Ni, Pb, and Zn) indicated low level of ecological risks in the region. Whereas, As and Cd, about 39 samples manifested as moderate or strong ecological risk. The indices of Hg were generally high, and the risk from Hg was found to be strong to very serious in more than half of the samples. The ecological risk of each heavy metal is shown in Fig. 7, while Table S9 shows the comprehensive analysis of the eight heavy metals.

The comprehensive analysis of the eight heavy metals showed that the proportion of samples with slight to moderate risk was 82.95% and that with strong to very serious risk was 17.05%. It was Hg and Cd that contributed the most to the potential ecological risk among the eight heavy metals.

Human health risk assessment

Daily intake The average daily intake of heavy metals in soil in the study area was evaluated. Table S10 shows the daily non-carcinogenic soil heavy metal intakes of both adults and children in this region, and Table S11 shows the daily carcinogenic intakes.

For adults, both non-carcinogenic and carcinogenic intakes were manifest as $ADD_{iing} > ADD_{iderm} > ADD_{iinh}$. For individual heavy metals, the non-carcinogenic intake followed the order of $Zn > Pb > Cr > Cu > Ni > As > Hg > Cd$, and the carcinogenic daily intake was $Cr > Ni > As > Cd$.

The situation in children was similar to adults; the daily intake by children was higher than that by adults.

Non-carcinogenic health risk The assessments of the non-carcinogenic risks are presented in Fig. 8a, b and Table S12.

Similar to daily intake, the non-carcinogenic health risks followed the order $HQ_{iing} > HQ_{iderm} > HQ_{iinh}$ in both

adults and children. The non-carcinogenic contributions from individual soil heavy metals followed the order As > Cr > Pb > Ni > Hg > Cu > Zn > Cd; of these, As, Cr, and Pb contributed over 95% to the HQ.

In adults, the HQ values of all the samples were less than 1, and the average and maximum values were 0.074 and 0.37, suggesting that adults were less likely to be affected by soil heavy metals in this area in terms of non-carcinogenic health effects.

The risks to children were higher than adults. The average HQ value was 0.52 with a maximum value of 2.6, and there were only 5 of all the 217 samples whose HQ values were over 1, indicating that the non-carcinogenic health risk caused by the soil heavy metals in this region had little impact on children overall, but some sites were associated with high risks.
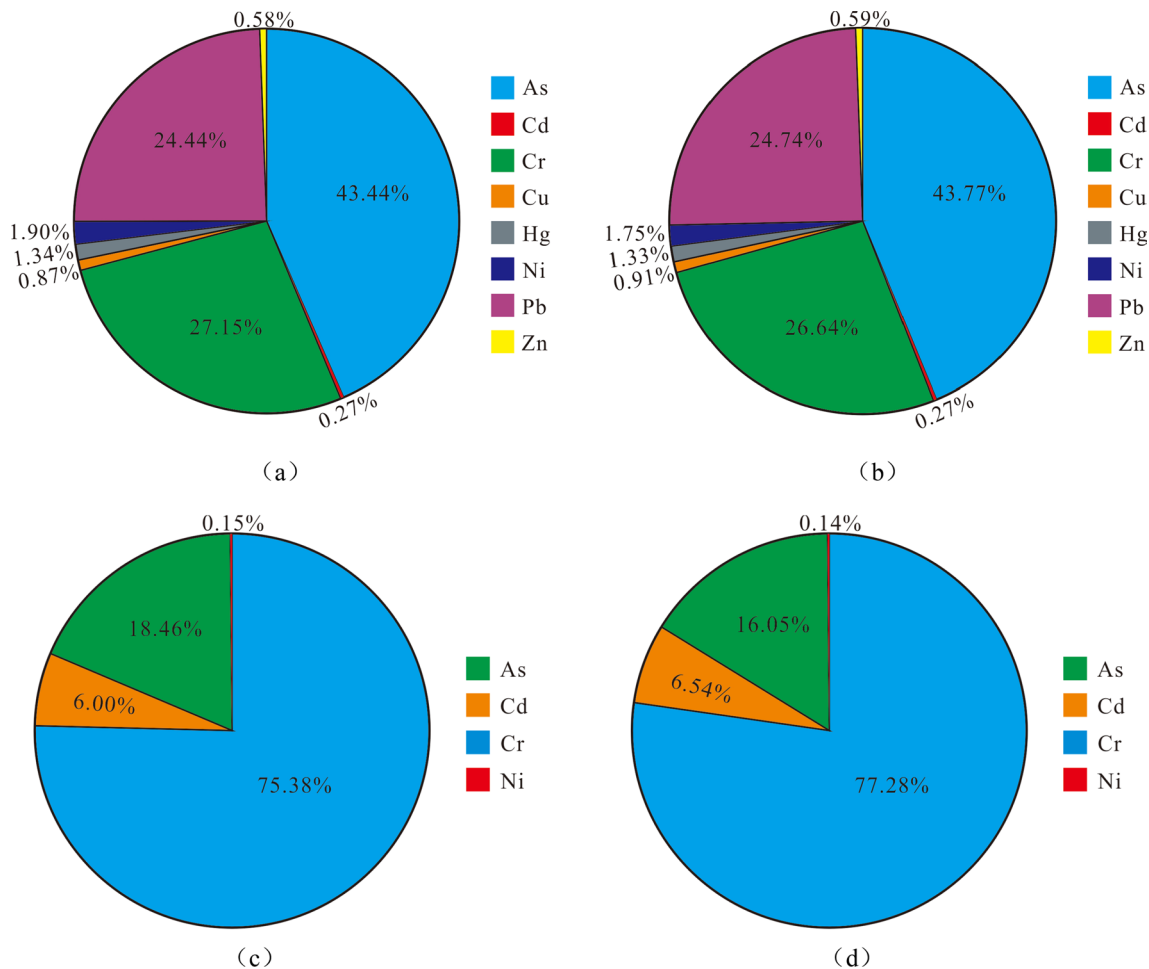

Fig. 8 HQ and CR contribution rates of soil heavy metals in adults and children. **a** HQ contribution rate of the eight soil heavy metals in adults. **b** HQ contribution rate of the eight soil heavy metals in children. **c** CR contribution rate of four soil heavy metals in adults. **d** CR contribution rate of the four soil heavy metals in children

Carcinogenic health risk The carcinogenic health risks were then assessed, which is presented in Fig. 8c, d and Table S13.

Identical to the non-carcinogenic risk, the carcinogenic risks in terms of the different intake pathways followed the order $CR_{iing} > CR_{iderm} > CR_{iinh}$ in both adults and children. The carcinogenic contribution rate from individual soil heavy metals followed the order $Cr > As > Cd > Ni$. In particular, Cr was responsible for over 75% to the CR.

As for adults, the average and maximum CR values were 6.5×10^{-6} and 5.2×10^{-5}, which were within the acceptable range of 10^{-4} to 10^{-6}. Therefore, the carcinogenic health risk to adults from soil heavy metals in this region was weak.

In comparison with adults, there were greater carcinogenic health risks among children. The average CR value was 1.7×10^{-5}, and the maximum value was 1.4×10^{-4}. There was only one sample with the CR value over 10^{-4}. Therefore, the carcinogenic health risks posed by soil heavy metals in this area were also low for children in general; however, children faced a greater risk than adults.

Agricultural security risk assessment

In the farmlands and orchards around this mining activity area, 20 samples were collected to conduct fractionation analysis of soil heavy metals. The mean values of the different speciations of each soil heavy metal were calculated, and the mobility factors of each soil heavy metal were then obtained (Table S14).

The mobility factors of these samples were calculated to assessed the risk of agricultural security, and this was used to speculate the risk for the whole region. The mobility factor of As was 0%, whereas that of Hg was 0.34%; that is, these heavy metals were not mobile enough in the soil to be utilized by crops. Notably, the mobility factor of Cd reached 50%, suggesting that Cd might exert a negative impact on the agricultural security of the region. The mobility factors of Pb, Zn, Ni, Cr, and Cu had a ranged from 3.75% to 8.33%, indicating that they had little influence on agricultural production.

Discussion

Sources of soil heavy metals

It is important to identify and address the sources of contamination to reduce the negative impacts of heavy metal pollution. Based on the results of the comprehensive analysis shown in the previous section, sources of soil heavy metals can be predicted in this mining activity area.

Ni and Cr were the main component in PC1, followed by Cu. The soil in this region had relatively low Ni, Cr, and Cu contents in comparison with the background values, as well as low CVs for these metals. Thus, there was a minimal level of contamination in the mining activity area caused by these three heavy metals to the soil. In addition, these results indicate that the metals associated with PC1 were not strongly affected by mining activities, and that the Ni, Cr, and Cu in the soil were derived from natural sources, mainly the soil parent materials.

The main heavy metals in PC2 were Hg, Pb and Cd. Of these, in comparison with the background concentration of this region, the average Hg content in the soil was over six times higher, and the CV of Hg was also a high level of 223.56%, indicating a strong influence from human activities. The average contents of Pb and Cd also were also higher than the background concentration and several sites in the mining activity area were polluted by them. Together, these results suggest that mining activities had tended to produce contaminants containing Hg, Pb, and Cd, and the regions enriched by these three heavy metals basically coincided. Therefore, the heavy metals relating to PC2 were derived from anthropogenic and mainly from mining activities in this region.

As was the main heavy metal in PC3, followed by Cu. All of the soil samples that were mainly collected from farmlands and orchards showed only one abnormal point with a quite high value of As, which meant that it was highly likely caused by human factors. Meanwhile, the pesticides and fertilizers contained As and Cu. Therefore, the heavy metals in PC3 were also attributed to an anthropogenic source; however, the main source was likely pesticide and fertilizer use rather than mining activities.

As shown above, Cu existed in both PC1 and PC3, with loadings of 71.2% and 33.4%, respectively. Cu was thus considered to have a mixed source, and was mainly originated from the soil parent material, with a smaller part derived from pesticides and fertilizers.

Zn existed in both PC1 and PC2, with roughly equivalent contents and loadings of 32.9% and 35.7%, respectively. The above conclusions regarding the sources of pollution observed in PC1 and PC2 suggest that the source of Zn was mixed; that is, part of the Zn was derived the soil parent material and part came from mining activities. In nature, Zn exists in the form of minerals that can enter the soil parent material over time via rock weathering; however, mining activities might also cause the enrichment of Zn in soil, which further supports the conclusion that the source of Zn was mixed.

Effects of mining activities on the accumulation and distribution of heavy metals

According to the above analysis, the heavy metals produced by mining activities in this region were mainly Hg, followed

by Cd and Pb, and then Zn. The areas enriched with these four heavy metals were mainly distributed around the mining activity areas. Among them, areas enriched with Hg, Cd, and Pb were highly similar; however, the distribution characteristics of Zn, which has a mixed source, differ slightly from the others.

The results of the contamination assessment of the soil heavy metals (Sect. "Degree of soil heavy metal contamination") show that, although there was no serious contamination of the soil, it had been significantly affected by mining activities. In particular, the CV of Hg reached a high value of 223.56%. In combination with the primarily source of Hg, it can be deduced that the accumulation and distribution of Hg had been greatly influenced by human activities, and particularly by the mining activities.

The potential ecological risk was high in this region due to the high enrichment and toxicity of Hg, and similar (but less strong risks) relate to Cd. The potential ecological risk associated with other soil heavy metals produced by mining activities was low. The specific harm of Hg to environment in this mining activity area should be further investigated.

In this mining activity area, the soil heavy metals derived from mining activities were not the major contributor to human health risks. The heavy metals that posed the greatest risk in this region to human health were Cr and As. Although Cr was mainly sourced from natural sources and its content in the soil was rather low, it posed quite high non-carcinogenic and carcinogenic health risks to the human body, and a similar conclusion was reached by a previous study (Yu et al. 2019). The health risks associated with As in this region, whether carcinogenic or non-carcinogenic, were mainly related to pesticides andfertilizers, and this is particularly true for the outlier sample with a high As content. Among the heavy metals produced by mining activities, Pb posed a relatively high health risk (non-carcinogenic) to the human body, while the risks caused by other mining-related heavy metals were not very high.

With respect to agricultural security, although the sample size is small, some inferences can be drawn. Hg was the main heavy metal produced by mining activities; however, although it had a high enrichment degree and ecological risk, its mobility factor was only 0.34% and it, therefore, had little impact on agricultural production in this region. Cd was also primarily produced by mining activities in this region, and its mobility factor reached 50%; therefore, it was easily absorbed and accumulated by crops. Further research can be done by collecting the crops or fruits in this region and testing the Cd content to evaluate the harm to agricultural safety more accurately.

In accordance with the distribution characteristics of the heavy metals in soil, we considered that the contaminants produced by mining activity only affected the soil surrounding the mining area and did not spread to other areas, such as rivers and the reservoir. Therefore, the ecological, human health, and agricultural security risks posed by the heavy metals originating from mining activities were limited in scope around the mining area.

Controlling soil heavy metal contamination

In the process of the science-based control of soil heavy metal contamination, it is both crucial to control pollution from the source (by purifying and treating the waste, liquid, and exhaust gas generated by mining activities) and to treat and rehabilitate the contaminated soil via appropriate remediation measures (Adnan et al. 2022).

With respect to source control, it is essential to resolutely implement the strategic deployment of green mines, strengthen the monitoring of emissions from mining activities, transform or close old and production facilities that are serious polluters, optimize and improve the production process, and strictly control the emission of pollutants (Wang et al. 2022a). Based on the current pollution situation in this region determined in this study, it is also important to strengthen monitoring of Hg, Cd, and Pb in the produced emissions. Emissions should only be allowed if they have been treated and meet specific standards. With adequate policy implementation, the production units meeting emission standards could be given certain economic rewards, while those that exceed the standards could be penalized according to the law.

At present, controlling the heavy metal pollution in soil mainly follows these two principles, one is to reduce the harm of pollutants and another is to ensure that the amount of pollution is reduced. The first principle means to reducing the bioavailability and mobility of contaminants in the environment, which can be conduct by changing the form of contaminants in the soil or through the interaction of contaminants with soil. In addition, the second refers to reducing the negative influence of the heavy metals, specifically by reducing the total amount of pollution through treatment from the soil to remove harmful substances. With respect to the soil heavy metal contamination in this mining activity area, it is recommended that the heavy metal-contaminated soil should be remediated by the passivation remediation technology (Adnan et al. 2022). With this technique, lime is used as an alkaline passivation agent to repair the contaminated soil. The application of this technique in this mining activity area would provide the following advantages: (1) the soil is relatively acidic (mean pH value of 5.38), and lime is an alkaline substance that can neutralize active acids in soil. Hydrogen ions are consumed and hydroxide ions are increased, which promotes the precipitation of oxides by heavy metal ions. The negative charge on the surface of soil colloids increases, and this enhances the chelating ability of heavy metal ions

in clay and organic matter or that of iron and aluminum oxides in the soil, thus ultimately affecting the adsorption and desorption of heavy metals. (2) In addition, hydroxide and carbonate produced by the hydrolysis of lime materials can form low solubility compounds, and this is achieved by hydroxide precipitation, carbonate precipitation, or via heavy metal oxides that have a strong affinity for the soil adsorption point. Such compounds reduce the activity of heavy metal ions. After remediation, the Hg, Cd, and Pb contents (particularly Hg) in the soil should be monitored, and reasonable measures should be taken to control pollution-related problems over time.

The As and Cr contents of the soil in this region should be given increased attention. Although the main sources of these two heavy metals were not mining activities, they had a great impact on human health. Cr was mainly originated from the soil parent material, and it might pose certain health risks to the human body, including endemic diseases. It is, therefore, suggested that the Cr content of the soil should be monitored in the mining activity area. In addition, the As content was mainly sourced from pesticides and fertilizers. Therefore, pesticides and fertilizers should be applied based on scientific guidance to minimize the accumulation and enrichment of As, thus reducing human health risks. It is recommended that the relevant departments could provide corresponding publicity and guidance regarding these measures.

Conclusions

The heavy metals produced by mining activities in the study area were mainly Hg, Cd, and Pb. These three heavy metals in soil in the mining area tended to be enriched, but serious pollution has not occurred throughout the entire region. The distribution of polluted areas was patchy, and pollution had not spread via the rivers and the reservoir to other parts of the mining activity area. Nevertheless, Hg and Cd produced by mining activities might pose certain ecological risks, Cd might further affect agricultural security in this region, and Pb was harmful to human health. However, the two heavy metals that had a relatively high negative impact on human health were Cr and As, which were not sourced from mining activities. The results of this research provide practical suggestions and useful guidance for controlling soil pollution, promoting ecological protection and restoration, improving the health of local resident, and ensuring safe agricultural production in river basins affected by mining activities areas. The water quality of rivers and reservoirs was not analyzed in this research, and we intend to do some research on heavy metal pollution in both water and soil in the future work to provide conclusions that are more comprehensive.

Declarations

Conflict of interest The authors have no relevant financial or no-financial interests to disclose.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate Not applicable.

Consent to publish The authors confirm that the work described has not been published before. All authors have approved the submission of this manuscript.

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